

N91-23060

CONTROL SYSTEM SOFTWARE, SIMULATION AND ROBOTIC APPLICATIONS

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ABSTRACT

The Goddard Space Flight Center (GSFC) has developed several computer programs that automatically derive and numerically solve the equations of motion for any multibody system. That is, any system that can be modeled as a collection of hinge connected rigid and flexible bodies acted upon by internal and external loads. During the past decade, these programs have proven to be the only logical method for reducing the cost of in-depth analysis for spacecraft, robots, and other complex mechanical systems. This paper provides an overview of associated modeling capability and its many applications. Several ongoing efforts to enhance existing capabilities and to apply evolving technology in and out of the aerospace industry are discussed. The man/machine interaction dynamics and performance (MMIDAP) project is a prime example, it is focused toward supporting designers of mechanical systems that are controlled by an operator's intelligent physical exertions. Medical industry involvement in this project is in a very real sense proving that technology transfer is a two way street. Many of MMIDAP's human performance and biomechanical analysis capabilities are a direct result of collaborations with the medical industry.

INTRODUCTION

The Technology Utilization Office, the Flight Telerobotic Servicer (FTS) project and the Office of Aeronautics, Exploration and Technology are all providing support for projects that utilize the capabilities of multibody modeling tools. This diverse support group has created a product development environment that is supportive of near-term NASA applications, far term NASA needs, and technology transfer initiatives into non-traditional application areas.

During the early 1960s, NASA satellite designers were conceiving and building spacecraft with innovative controllers faster than project support engineers could derive, code, and debug system stability and performance analysis programs. In an attempt to keep pace with need and to reduce associated cost, several efforts were initiated within the aerospace community to create a general purpose design and analysis capability. While several groups developed in-house propriety codes with impressive capability, NASA/GSFC created and brought the programs NBOD & DISCOS into the public domain. A recent review of these programs and their current capabilities is to be found in [1]. Unknown to the aerospace community, at the time, researchers at the University of Iowa were also actively engaged in developing similar capabilities for the mechanical engineering community. While GSFC supported the aerospace community, Iowa supported the machine and vehicle design community. The software of both groups is used internationally. Both development groups are now collaborating to enhance their respective capabilities. This enhancement effort is lead by a research team associated with the National Science Foundation (NSF), U.S. Army Tank Automotive Command (TACOM), NASA/GSFC cosponsored Industry/University Cooperative Research Center (I/UCRC) at the University of Iowa and its supporting membership of about 30 government and industrial laboratories. The research objectives of the I/UCRC are defined in [2].

One major trust of the collaborating researchers is to provide a reliable modeling and simulation capability for supporting the concurrent engineering systems that are presently being implemented throughout this nation's manufacturing industry. This activity is motivated by the general agreement that about 70% of a product's life-cycle attributes are defined by decisions made during the concept exploration phase of design. As a result, early in depth analysis is critical to impacting design decisions. Design changes made after this phase have a high ripple effect on project cost.

An analysis capability that can quantify operator performance vs. design alternatives during the early design phase is needed for both ground and space based applications. The GSFC's MMIDAP project supports this goal. It is directed toward machines that are controlled by a human operator's intelligent physical exertions. These tools will allow designers to quantitatively introduce an operators's physical and cognitive limitations into design tradeoff decisions (for more detail see [3] and [4].) GSFC's supported MMIDAP capability will be developed in a generic manner so that it can be applied to a broad range of aerospace, machine design, ergonomic, physical therapy and rehabilitation engineering problems.

NASA NEEDS, STATE OF THE ART

The final report of the 1985 Integrated Ergonomic Modeling Workshop [5] contains a detailed review of pre-1988 software capability along with a list of recommendations for future research. It specifically remarks that "there is a paucity of dynamic interface models" and that "an integrated ergonomic model is needed, feasible, and useful." The report's review of existing capability demonstrates that ergonomic modeling software has been primarily developed to support aerospace cockpit design, design for product maintainability, and whole body dynamics associated with automotive vehicle crash and pilot ejection. Some work exists under the general heading of optimization of sports motion. however, there is virtually nothing to support designers who must evaluate man/machine interaction dynamics and performance with or without survival gear, in hostile environments, on earth, or in the reduced gravity environment of space.

A MMIDAP analysis capability is of critical importance to NASA. Space Station Freedom (SSF) is to be a long life mission. External maintenance of the SSF will be required for several decades. What cannot be accomplished via robotics will have to be done via extravehicular activity (EVA). As identified in the S-SF Fisher - Price report [6] a major goal is to reduce EVA activity by exploiting the fleet of U.S., Canadian, and Japanese robots for carrying out the maintenance and replacement of on-orbit equipment. For this strategy to be effective the orbital replacement units ORU's must be designed for commonality in order to maximize the use of robotics. The cost prohibitive need to laboratory test replacement scenarios for each of the approximately 450 different ORU types must be minimized. The development and use of a MMIDAP analysis capability is, to this author, the only viable option.

ANTHROPOMETRIC, BIOMECHANICAL, AND HUMAN PERFORMANCE DATABASES

The MMIDAP project research group feels that it is time to take stock of present analysis methods and their associated data determination needs. A dedicated emphasis on developing the infrastructure for the systematic, engineering approach to solving human system problems and recognizing current limitations is needed.

The National Library of Medicine (NLM) is currently undertaking a first project at building a digital image library of volumetric data representing a complete normal adult human male and female [7]. This "Visible Human Project" will include digital images derived from photographic images from: cryosectioning, computerized tomography, and magnetic resonance imaging. NASA/GSFC is complementing this effort with a "whole body digital mapping project". The GSFC project seeks to develop a hierarchical tree of biomechanical and human performance analysis capability vs data availability. The output of this project will be used by the MMIDAP project to both define objectives and recognize analysis feasibility limits. This is a cooperative project involving: biomechanics groups from the University of Iowa and Case Western Reserve University, human performance specialists from the University of Texas at Arlington, and anatomists from the University of Colorado at Denver. The objective is for the analysts to define data needs while anatomists are to define if it is feasible with modern technology to provide the requested data as a by-product of the "Visible Human Project." Details will be defined in the project's final report [8].

One major problem with existing biomechanical data is that it comes from so many different sources with almost as many different measurement reference frames. The NLM's Visible Human Project is presenting the biomechanics community with a unique opportunity to fill gaps and to obtain a consistent reference source of fundamental biomechanical data. GSFC's whole body digital mapping project seeks to precisely define what

should be measured and how it is to be databased.

Biomechanical data alone is not sufficient for man/machine interaction dynamics and performance analysis. The problem also needs human function and human performance information. Reference [9] provides a review of ongoing work in the quantitative measurement, assessment, and databasing of human performance at the Human Performance Institute (HPI) at the University of Texas at Arlington. This work was originally focused toward the field of Physical Therapy and Rehabilitation Engineering. It is now recognized that HPI's databased information and measurement systems are identical to what is needed to support the MMIDAP project.

MAN-IN-THE-LOOP SIMULATORS FOR COMPLEX MECHANICAL SYSTEMS

Major advances in formulating the mathematical equations needed to simulate complex mechanical equipment along with the availability of low cost parallel processor computers have provided a unique opportunity to create low cost real-time simulators for complex mechanical equipment with man in the control loop. Simulators accept real-time man in the loop commands, graphically create a simulated visual environment, and drive other laboratory devices to create a simulated vibrational and audio environment. Stress and load information for machine components can be obtained directly from the simulator. Qualitative control system feel information can be obtained from operator comments. Human performance data can be obtained by monitoring operator response in the simulated environment. The ability to simulate in real-time all gyrodynamic loads and machine force feedback control loads that operators must respond to sets this new effort apart from that available via aircraft flight trainer technology.

A first step toward developing a simulator capability for complex human operated mechanical systems was taken at the University of Iowa with the development of a simulator for a J.I. Case backhoe. The ongoing second step is to create the Iowa Driving Simulator in 1991 [10] and the final step will be to develop the Department of Transportation's National Advanced Driving Simulator [11] in the mid 1990's.

INTEGRATED MUSCULO-SKELETAL MACHINE DYNAMICS EQUATIONS OF MOTION

The exact same methods and computer programs that are used to create real-time man in the loop simulators for mechanical systems can be used by biomechanical groups to simulate human body response. An overview of existing pre-1990 multibody modelling capability is provided in [12]. In the late 1980's several international groups independently discovered that equations of motion could be rederived in such a manner that computational speed could be greatly enhanced. New implementations with improved speed and modeling capability are now in the beta-site testing stage. The GSFC/Cambridge Research program Order N DISCOS is defined in [13] and Iowa's I/UCRC Order N² program NGDC is defined in [14]. For biomechanical applications several modeling limitations have been recognized by Frisch, Turner, and Chun. Plans are now underway to enhance Order N DISCOS program accordingly.

Multibody simulation models have been successfully used to model certain classes of musculo-skeletal systems. As stated above, modeling weaknesses do exist and these must be recognized before one attempts to use multibody tools for general biomechanical application. The dynamics analysis of mechanical systems is dominated by the need to solve the forward dynamics problem. That is, given a prescribed set of internal and external loads, predict system response. Attempts to perform forward dynamics analysis with neuro-musculo-skeletal systems is usually stopped by one's inability to mathematically characterize the human's cognitive processes that generate the neural activation signals that stimulate the body's musculo actuator system.

The MMIDAP project recognizes this fundamental limitation, instead it concentrates on the inverse dynamics problem. Graphical animation and laboratory testing techniques exist for obtaining an estimate of human dynamic response for a broad range of activities. If sufficient information can be obtained

(displacement, rate, acceleration, and external loads) then inverse dynamics methods can be used to predict what the resultant musculo actuator loads had to be to produce the defined input response. These results can then be compared with known human performance information to determine if predicted musculo response required by a machine operator is within the limits of capability for the machine designer's target operator population group.

MUSCLE MODELING AND LOAD SHARING

Detailed neuro-musculo-skeletal modeling of the human system or any of its subsystems is an extremely complex problem that is beyond today's state-of-the-art capability. The First World Biomechanics Congress in August 1990 had over 80 oral presentations on the subjects of multiple muscle systems, biomechanics and movement organization. Formal reports on 46 of these presentations have been collected in [15]. From these reports and others presented at the Congress it is clear that muscle dynamics and neuro-musculo-skeletal organization and movement modeling is a subject that will occupy researchers for many more years.

Complexities associated with modeling muscle contraction dynamics are matched by the problem of muscle load sharing. The presence of redundant muscle actuators at virtually every anatomical joint implies that rules must exist for defining how muscles will share the work load. Ref. [16] provides an extensive summary of ongoing research in muscle load sharing at the University of Wisconsin at Madison. An understanding of muscle load sharing is needed to explain why certain design options or operational scenarios have the potential of causing machine induced discomfort, fatigue, pain, or trauma.

PREDICTION OF HUMAN MOTION

One fundamental difference between repetitively testing human subjects and repetitively testing mathematical models is that the human's response is nonrepeatable. The modeling goal for the prediction of human performance can therefore only be that the predicted motion be physically reasonable. Predictions and reasonable variations around them should be viewed as defining an envelop of possible human response. With this goal in mind simplified motion prediction algorithms can justifiably be introduced into a human motion prediction capability. The program JACK [17] has several unique features that make it ideal for the MMIDAP application. Figure positioning by multiple constraints is a capability that allows users to specify trajectories at several body fixed points (hand, feet, torso) and to then have motion trajectories for all other points predicted. Strength guided motion is a capability that uses human strength and comfort data for the motion prediction process. JACK uses a blend of kinematic, dynamic and biomechanical information when planning and executing a path. The task only needs to be described by a starting point, ending position, and external loads such as gravity and weights to be transported.

MAN/MACHINE DYNAMIC INTERACTION, ITERATIVE REFINEMENT

The output of the program JACK is animated human system response. As for any engineering analysis study, the physical realizability of predicted response must always be checked. This is done by viewing animated response and resultant joint behavior. Weighting factors within the JACK program allow user's to tune predictions to bring them into the realm of physical realizability for the particular population group under study (old, young, normal, handicapped, etc.) As a further check JACK's predicted joint response information is used as input to the program Order N DISCOS. This program includes a detailed dynamics model for the machine and the operator's musculoskeletal system. The associated equations of motion for the multibody model are exact, relative to the laws of Newtonian mechanics. Order N DISCOS's inverse dynamics capability is then used to obtain a refined prediction for resultant joint loading. Differences between JACK and DISCOS resultant load predictions stem from the simplifying assumptions within JACK's motion prediction algorithms and man/machine interaction dynamics. The output of Order N DISCOS becomes input to the program defined in [16] to predict muscle load sharing. If resultant joint loading and muscle load sharing predictions are acceptable then motion and load prediction information is used as input to the human performance database at the HPI. The output of this step provides another assessment of physical realizability. If results violate physical realizability JACK weighting factors can be adjusted and the process

repeated.

The iterative refinement process is used until the successive approximations strategy converges to acceptable results. The predictions will either confirm that man/machine interaction is acceptable or that some human performance parameters exceed databased norms. Machine design changes can be refined until acceptable performance measures are achieved for the machine operator's population group.

TARGET NASA SPINOFF APPLICATION

GSFC's Office of Commercial Programs is strongly supportive of efforts to transfer aerospace developed technology. The following technology transfer initiatives are currently being pursued:

- o The underlying technology of real-time man in the control loop simulation is the enabling technology needed to build simulators for the ergonomic design of a man/machine interface. These facilities will support physiological and cognitive research related to human operation of mechanical systems with an emphasis on automotive vehicles. Issues associated with operator performance under the influence of alcohol, drugs, sleep denied fatigue, etc. can all be investigated in a simulator without the danger of life threatening injury to the test subject.
- o The ability to account for operator population group in the design process provides an ability to determine if a handicapped person has the physical and cognitive resources necessary to operate a particular machine. This capability not only opens the door to the job placement for the handicapped problem, but also allows machine designers to identify and remove design features that inhibit operation by the handicapped.
- o Exercise equipment can be viewed as human operated machines. Since operators tend to operate these near the limit of their physical resources, it is important that they be carefully designed. They must exercise particular muscle groups while not causing physical injury to other muscle groups or associated joint complexes.
- o Bone and muscle atrophy is a major problem for space missions. If the body senses that either bone or muscle is not needed it is absorbed by the body. To counteract this problem an exercise program must be designed to stress both bone and muscle. Proposed exercise systems can be evaluated relative to each astronaut and alternative exercise scenarios can be compared via quantifiable performance measures.
- o Physical therapy is a slow process that is difficult to measure in a quantifiable sense. Techniques used to validate MMIDAP capability will be directly applicable to the measurement of rehabilitation progress. The MMIDAP capability itself can be used to set exertion limits for recovering patients and machine operators.
- o Rehabilitation engineers develop a wide range of devices and prosthetics so the injured and disabled can recover lost performance and prevent further injury. Both active and passive prosthetic devices can be viewed as human operated machines that need MMIDAP design analysis.
- o Functional neural stimulation (FNS) is currently being used to stimulate both upper and lower extremity muscles of spinal cord injured patients. The objective of FNS research is to design a control system for the coordinated electric stimulation of those muscle groups needed to provide a standing, walking and grasping capability. Patient safety considerations demand that proposed FNS control strategies be evaluated via computational analysis before they are administered. An ability to measure and quantify patient progress is another need. The MMIDAP project will support both needs.

- o Occupational and sports related trauma is a serious problem when workers or athletes carry out strenuous repetitive actions or intentionally shock their musculoskeletal system; eq. carpal tunnel syndrome, white finger, and tennis elbow. A better understanding of how trauma causing forces and moments develop is needed to suggest less stressful body motion strategies.
- o Biochemists are attempting to better understand how drugs work within the human body. This quest leads to the need to model the molecular dynamics of protein enzyme reactions. The program Order N DISCOS is currently being beta site tested for this application at Dupont with the assistance of Cambridge Research. Attempts to use the program NBOD for this application are outlined in [18].

SUMMARY

This paper has reviewed all essential existing capability needed to create a man/machine interaction dynamics and performance (MMIDAP) capability. The multibody system dynamics software program Order N DISCOS will be used for machine and musculo-skeletal dynamics modeling, the program JACK will be used for estimating and animating whole body human response to given loading situations and motion constraints,, the basic elements of performance (BEP) task decomposition methodologies associated with the Human Performance Institute's BEP database will be used for performance assessment, and techniques for resolving the statically indeterminant muscular load sharing problem will be used for a detailed understanding of potential musculotendon or ligamentous fatigue, pain, discomfort, and trauma. The envisioned capability is to be used for mechanical system design, human performance assessment, extrapolation of man/machine interaction test data, biomedical engineering, and soft prototyping within a concurrent engineering (CE) system.

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